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The High Speed Navy: Vessel Motion Influences on Human Performance

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The High Speed Navy: Vessel Motion Influences on Human Performance

ABSTRACT

This paper presents the recent results from an ongoing analysis of the effects of high speed naval operations on the performance, comfort, and safety of crew and passengers. A 127 meter trimaran, the *Benchijigua Express*, which is similar in hull design to the General Dynamics Littoral Combat Ship (LCS) vessel, was investigated for motion-induced interruptions, motion sickness, and biodynamic feed-through to manual tasks. Data were obtained on two 2-hr transits per day for a total of 86 transits during February and March 2006. Survey questionnaires were obtained from nearly 2000 passengers. The motion effects on manual dexterity were negligible, but motion sickness symptoms were reported by a majority of the passengers. The capability to manage the motion sickness issue for unadapted passengers may be important for the effective use of LCS to transport ground combatants and for Sea Basing concepts.

INTRODUCTION

This is one of a series of studies on the effects of high speed naval operations on crew performance and passenger well being. The results are intended to be relevant to the Littoral Combat Ship (LCS) program. There are two hull designs under construction for LCS, the General Dynamics LCS trimaran (or "stabilized monohull") and the Lockheed-Martin semi-planing monohull. The study reported here summarizes the findings from an evaluation of motion effects onboard the *Benchijigua Express*, a 127 meter trimaran built by AUSTAL Ships and operated in the Canary Islands by Fred.Olsen SA Ferry Lines. NSWC Carderock Division previously evaluated the global structural response and seakeeping characteristics of this vessel (Grassman, Gaies, & Lewis, 2005). The *Benchijigua Express* (see Figure 1) is capable of transporting up to 1,300 passengers and 340 automobiles at speeds up to approximately 40 knots.

Figure 1. Fred.Olsen SA *Benchijigua Express*, March 2006.

Working in a moving environment can lead to performance decrements for several reasons, including motion sickness and concomitant reduction in motivation, as well as direct biomechanical influences (Wertheim, 1998). The research questions addressed in this study were: 1) what is the incidence of motion sickness and motion induced interruptions; 2) what are the effects of high speed motion on manual dexterity tasks; and 3) what are the major attributes of ship's motion that affect the passengers.

METHODS

Instrumentation

Vessel motion data were obtained from sensors developed and installed by NSWC Panama City at four locations on the Upper Deck (main passenger deck) and two locations on the Auto Deck (representative of the LCS GD Mission Bay). Selection of locations was based primarily on habitation and suspected susceptibility to slamming events (forward half of ship). The two primary upper deck instrumentation packages (indicated as red circles in Figure 2) each consisted of a GPS control box, two six-degrees of freedom (6DOF) accelerometers, two video cameras (see Figure 3), and a video recorder/titler unit).

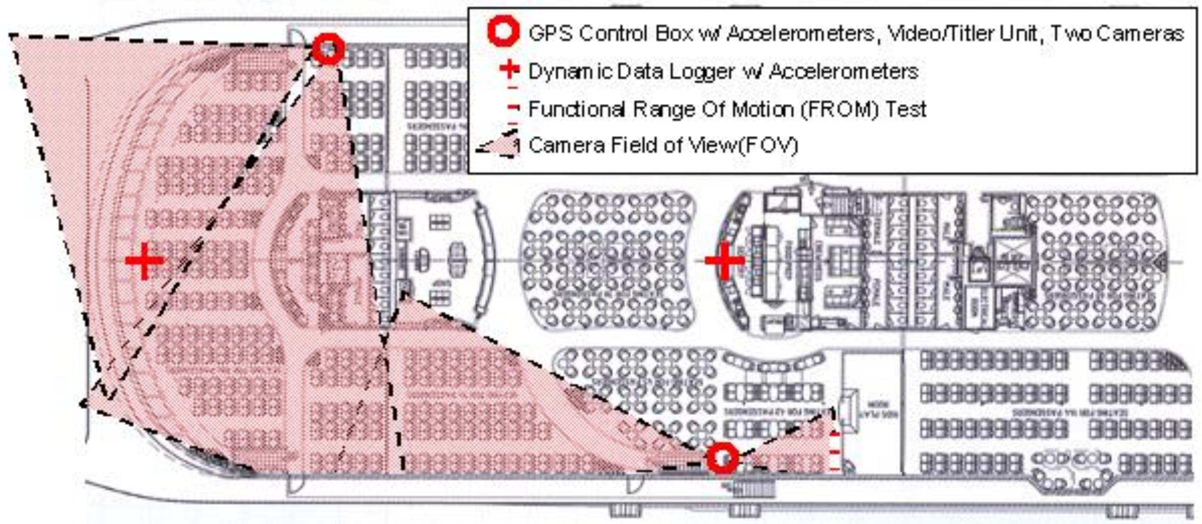

Figure 2. Upper deck instrumentation layout. Bow is to the left

Prior to installation, this equipment was modified to run on the ship's 240VAC European power. To ensure compliance with Spanish privacy laws, all video camera angles were pre-approved by Fred. Olsen S.A., audio data was not collected, and placards (written in English, Spanish, & German) were located throughout the ship to provide passengers with full knowledge of the presence of cameras in designated areas. Four additional 6DOF accelerometers connected to battery-powered Dynamic Data Loggers (DDL) were installed in two upper deck locations along the ship's centerline (indicated as red crosses in Figure 2). These DDLs received GPS time stamps through a radio frequency (RF) (900 MHz Carrier Freq) connection to the GPS control boxes.

Figure 3 - Port Side, Upper Deck Camera and RF Antenna Assembly

This design ensured that all vessel dynamic data were time synchronized and could be linked to all other collected data. A third GPS control box was installed on the Auto Deck at the bow/centerline of the ship and RF linked to two DDLs located at Longitudinal Center of Gravity (LCG). All dynamic data were collected at a sampling rate of 750 Hz, anti-aliased internally at 250 Hz. All test instrumentation was secured in black pelican cases (Figure 4) for aesthetics and to reduce the possibility of passenger tampering.

Figure 4 - Starboard Side, Upper Deck Instrumentation Package

The ship had two devices for measuring relevant seaway data accurately. The first was a Miros WAVEX system, which uses the sea clutter image from standard marine navigation radar to monitor and record a range of ocean wave data. The second was a TSK Wave Height Meter system, which uses a bow-mounted microwave sensor unit to monitor significant wave height and period. Despite repair efforts by Austal that started before the test team arrived, the WAVEX system was inoperable until the last day of testing. Furthermore, the TSK system had no recording capability. To ensure relevant seaway data was collected, and with permission from the onsite Austal representative, the NSWCPC test team modified the bow-mounted GPS control box to receive and store data from the TSK. Also, the Captain agreed to supplement the seaway data by maintaining a log of observed seaway conditions.

Following the ten-day detailed study, video recording units, centerline DDLs, and car deck dynamic instrumentation were removed. The two primary Upper Deck instrumentation packages (indicated as red circles in Figure 2 above) and the modified TSK remained on board for an additional four weeks, continuing to collect data during each 2-hr transit.

Survey Questionnaires

Questionnaires asked about passengers' experience aboard ships in the past 30 days, the experience and severity of motion induced interruptions (MII) while underway, the Motion Sickness Assessment Questionnaire (MSAQ) (Gianaros, Muth, Mordkoff, Levine, & Stern, 2001) and participants' comments regarding the ship's motion.

The questionnaires were revised in several ways to accommodate the needs of this study. A graphic of the *Benchijigua Express* seating areas was shown on the last page of the questionnaire and participants were asked to identify the location in which they were seated. The questionnaires were made available in three languages by translating from English into Spanish and German to accommodate the variety of passengers commonly served by the Benchijigua. The translations were done by international students and faculty at the Naval Postgraduate School.

Manual Dexterity Test: The Functional Range of Motion (FROM)

The FROM is an industrial skill assessment device, essentially a peg-placement task that tests manual speed and accuracy. Volunteers in the age range 18-35 were solicited from among the *Benchijigua Express* passengers. They participated two-at-a-time to provide competitive incentive. Prizes were awarded for best overall performance each day. Participants were screened and disqualified if medicated, intoxicated, or not representative of military personnel based on physical fitness or age. The measure of performance is total time to transfer a complete set of pegs. Researchers timed each participant using a stop watch. The FROM test was administered in both a standing and a squatting position, based on preliminary analysis of similar tasks on LCS mission modules (see Figure 5). The hypothesis was that MII events and/or direct biodynamic feed-through from vessel motion would interfere with the manual performance.

Figure 5. The Functional Range of Motion (FROM) Test in two positions.

Procedures

DAILY DATA COLLECTION SCHEDULE

During the period of this study (February -- March, 2006), the *Benchijigua Express* operated between three of the Canary Islands, Tenerife, La Gomera, and La Palma. Each day the Benchijigua started in La Palma at 0800 and arrived at Los Cristianos, Tenerife at 1000 (a distance of approximately 67 nautical miles). Each evening, the return trip launched from Tenerife at 2000 and arrived at La Palma at 2200. Additionally, *Benchijigua Express* made six half-hour trips each day between Tenerife and La Gomera. Since the onset of motion sickness typically does not occur until after the first half-hour of a sea voyage, data were not collected on the La Gomera transits, but only during the two 2-hour Tenerife/La Palma transits each day.

DATA COLLECTION PROTOCOL

Approximately half-way through each transit, one hour after departure, the Fred Olsen Lines study coordinator distributed survey questionnaires to all passengers who were willing to participate in the study. This process required approximately 20 min, depending on the number of passengers. Immediately thereafter, the Captain's log data were solicited from the vessel's Captain on the Bridge. The Captain's Log asked for estimated wave height, wave direction relative to the ship, wind, and any other environmental or equipment factors that might influence ship motion during the transit.

The questionnaire surveys were collected when the vessel was approximately 15-min from destination (after approximately 1 hr and 45 min into the transit).

The vessel's ride motion control system was operating during the study.

During the ten-day detailed study, the upper deck instrumentation packages were checked to ensure that they had turned on automatically at the beginning of each transit. Fresh lithium batteries and compact flash cards were installed each day in all remote DDLs, and new videotapes were placed in all four video recorder units. During the "break" between each AM and PM transit, all data were archived from the morning transit and from the previous day's evening transit. The TSK recorder required manual initiation each day, so during the 4-week remote study, this task was done by the ship's engineer.

DATA REDUCTION PROCEDURES

The following analyses were performed on data collected during each 2-hr transit:

- Root-Mean-Square (RMS) analysis
- Plotted 15-second RMS and Peak G values for vertical sensor data
- ISO 2631 Part 1 (weighted for MSI) analysis
- Video analysis: Every MII captured on video was categorized by: duration (recovery time), number of people affected, original subject position (sitting, standing, etc.), original brace position (leaning,

using hand hold, etc.), criticality of any injury, ability to continue immediate task. A DVD was created linking each MII video clip to its associated dynamic data and category.

- Plotted time histories and peak Gs for sensor data corresponding to observed MIIs
- MII "Graham tipping equations" analysis and compared predictions with the MIIs observed in the video data

Subsequent analyses were conducted using SPSS (version 12) and Microsoft Excel software packages.

RESULTS

Data Description

Data were collected from 1,994 questionnaires between February 1 and March 29, 2006, in 86 data collection periods. In most cases, there were two data collection periods per day, the “morning” transit (approximately 0800 to 1000), and the “evening” transit (approximately 2000 to 2200). Based on observation by the researchers and confirmed by data retrieved from the United Stated Naval Observatory (http://aa.usno.navy.mil) the morning transits took place in daylight conditions, but it was dark shortly after launch during the “evening” transits. The crew and passengers had virtually no visual information about the horizon or the seas, or other earth-fixed reference during the evening transits.

MOTION SICKNESS ANALYSIS

The reported total MSAQ index ranged from 11.1 (minimum of the test) to 100 (maximum) (mean=22.5, median=15.8). The MSAQ has four subscales: G (gastrointestinal), C (central), P (peripheral), and S (sopite syndrome). These four are summed to give the Total MSAQ score.

During the test periods the mean vertical RMS acceleration at the forward sensor, averaged per 15-second intervals, was 0.0183 [g] (median=0.015 [g]). These levels are relatively low, compared to the acceleration levels used in experiments on Motion Sickness Incidence (O’Hanlon & McCauley, 1974), but the level of MSI also was lower onboard the *Benchijigua Express*

The passengers’ experience with ship motion was categorized as “Inexperienced” if they traveled aboard ship 0 or 1 times during the prior month, “Some experience” (2 to 8 times), or “Highly (Good) experienced” (more than 9 times). Almost half of the participants were inexperienced, and, not surprisingly, they exhibited the most severe symptoms of motion sickness (See Figure 6). The most experienced group had the lowest MSAQ scores, consistent with the adaptation process.

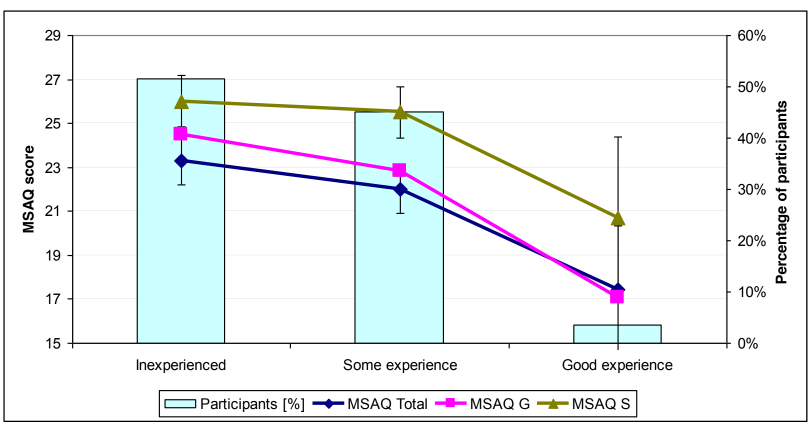

Figure 6: **MSAQ scores per passengers’ recent experience with ship motion.**

The differences in MSAQ Total in all cases were statistically significant (one-sided t-test between "Inexperienced" and "Some experience", n=786, t=1.653, p=0.05, one-sided t-test between "Some experience" and "Highly experienced" n=60, t=2.299, p=0.01). The results were slightly different for the MSAQ S (sopite syndrome index) where the difference between the inexperienced and the passengers with some experience was not significant.

As mentioned previously, the morning and evening test periods had different light conditions. The MSAQ scores for the morning and evening transits are depicted in Figure 7.

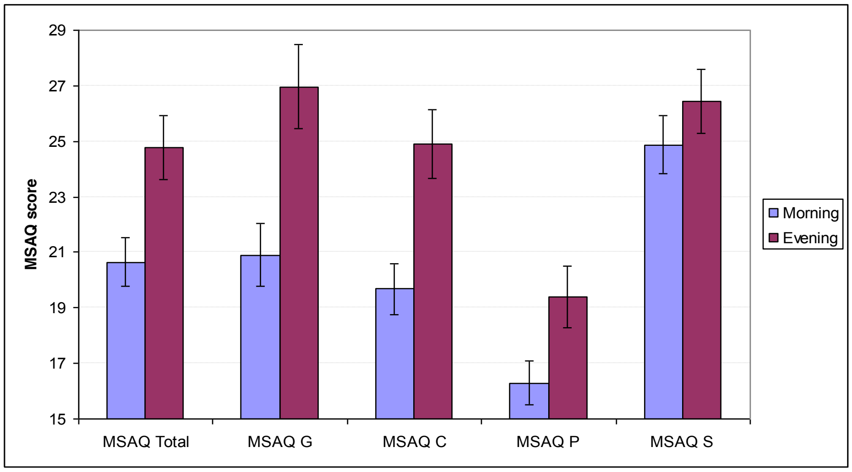

Figure 7: **Mean MSAQ scores per "Morning" / "Evening"** trip.

Scores on all four subscales of the MSAQ were significantly higher during the "Evening" trips (Total MSAQ, n=875, t=1.721, p<0.001; MSAQ G, t=6.385, p<0.001; MSAQ C, t=6.773, p<0.001; MSAQ P, t=4.589, p<0.001; MSAQ S, t=1.966, p=0.05), even though the mean vertical accelerations measured at the forward sensor were significantly decreased in "evening" data collection periods ("morning": mean RMS acceleration=0.017 [g], "evening": mean RMS acceleration=0.015 [g], one-sided t-test, t=2.737, p=0.003). The smallest difference between morning and evening MSAQ scores occurred in the S (sopite) scale.

Ship's heading relative to the seas affects the frequency and amplitude of ship's motion. The data were categorized for seas relative to ship's heading in five categories (HEAD, BOW, BEAM, QUARTERING, and FOLLOWING). Figure 8 depicts the reported mean MSAQ scores by relative heading. The acceleration values shown in the figure are the mean vertical RMS acceleration in [g] measured at the forward sensor. The MSAQ scores were lowest in BEAM seas and higher with HEAD, BOW, and FOLLOWING seas.

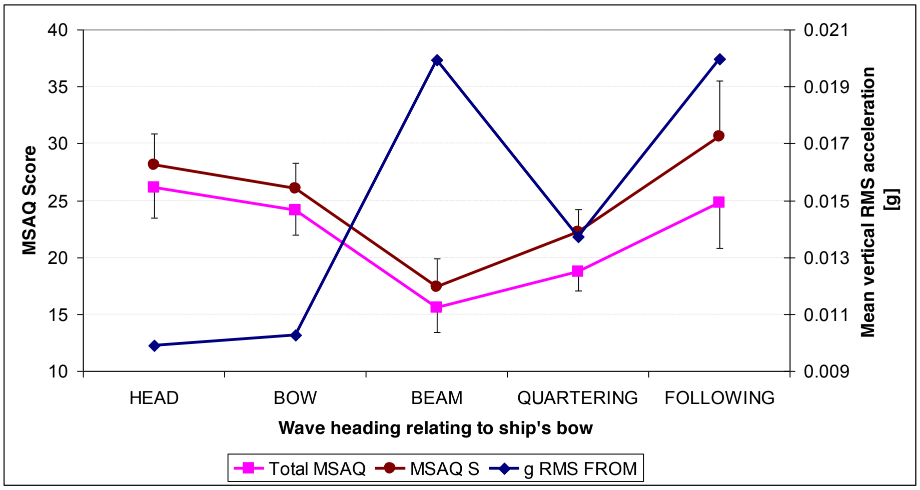

Figure 8: Mean MSAQ scores versus relative wave heading

The following diagram, Figure 9, depicts the percentage of participants who reported any kind of motion sickness symptom (Total MSAQ score>11.2), and the corresponding findings for the participants with increased symptom levels (score > 20 and score > 30) for the five categories of relative heading.

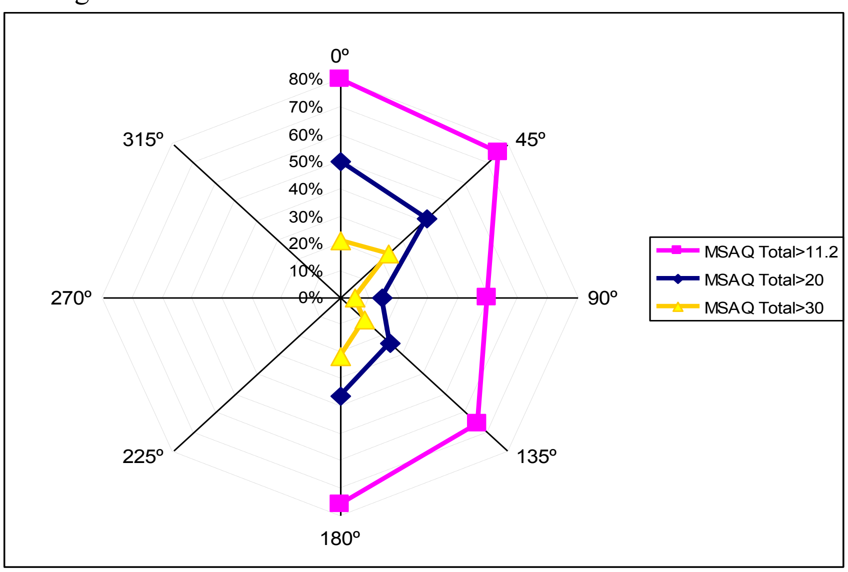

Figure 9: Percentage of participants per severity of Total MSAQ scores and relative heading of seas.

Again, the BEAM relative heading was associated with less motion sickness compared to HEAD, BOW, or FOLLOWING headings.

In nearly all transits, the mean predicted Motion Sickness Dose Value (MSDV; ISO 2631-1) percentage of participants was at approximately the 5% level, that is, 5% of the population would be predicted to experience emesis in a two-hour exposure. Actual MSI cannot be estimated accurately for reasons: (1) the MSAQ does not score emesis directly; and (2) we have no data on passengers who refused to participate in the survey, therefore we cannot compute MSI. When less severe motion sickness symptoms are considered, i.e., MSAQ scores of >20 and >30), the current data show that a much larger percentage of the sample is affected by motion sickness symptoms, on the order of 60% to 90% over the transits. Although crew members were not tested in this study, a much lower percentage of motion sickness (near zero) would be expected for an adapted crew and our observations were consistent with that view.

MII ANALYSIS

MIIs were defined in the questionnaire as:

> interruptions in your balance, movement, or task performance, caused by ship's motion. If standing, an MII could be slipping, sliding, losing your balance, not being able to walk, or having to grab hold of anything firm to continue conducting your task. If seated, an MII could be holding your chair so as not to slide, holding onto objects to keep them from falling off a table, or unusual difficulty in using your computer keyboard or mouse. In general, whenever the ship's motion makes you stop what you have been doing, even for a short amount of time, it is an MII.

The mean number of MIIs reported during each transit is depicted in Figure 10 as a function of relative wave heading.

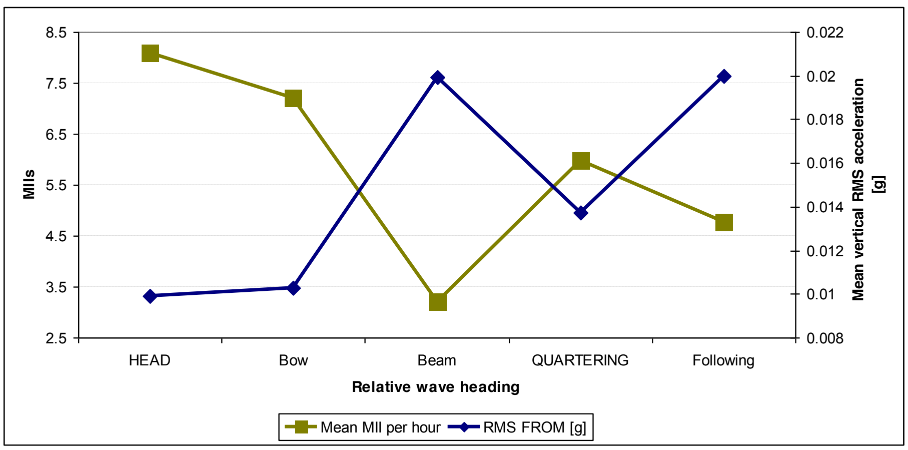

Figure 10: MIIs per hour underway hour versus relative wave heading.

The mean number of MIIs was lowest with BEAM seas and highest with HEAD seas. This result was obtained despite the fact that the vertical RMS acceleration, also shown in Figure 10, was high during BEAM seas. It remains to be seen whether the stabilized monohull design, which limits roll displacement, was the basis for this finding.

One type of MII is when an individual has to hold onto something to maintain their balance. A significant percentage (39.2%) of the participants reported that this type of MII occurred at some time during their transit. The percentage of reported balance issues was larger during evening (43.2%) compared to morning data collection periods (33.1%). The reason for this finding is unclear, but several factors may have contributed -- increased fatigue, higher proportion of alcohol consumption, and reduced external environment light conditions (lack of visual input – horizon).

As shown in Figure 11, the percentage of participants who reported that they had to hold on to something to keep their balance (because of ship's motion) was found to be dependent on relative wave heading. In general, following seas decreased the "hold on" balance incidents.

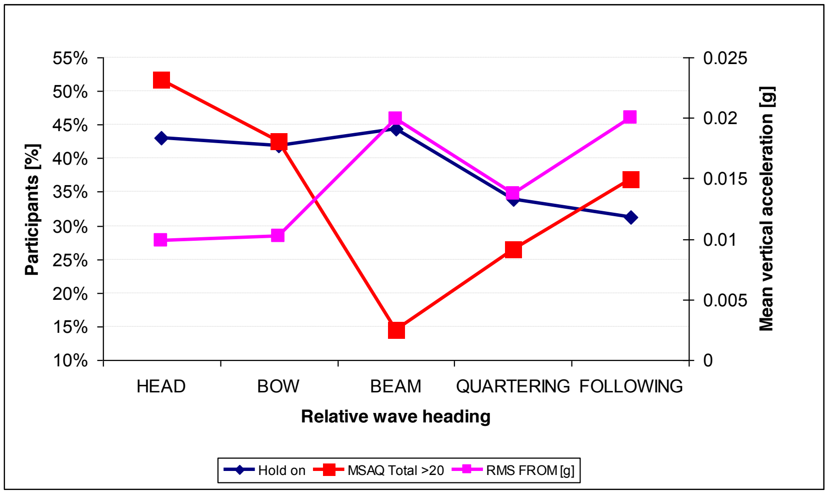

Figure 11: Participants that had to hold on to something to keep their balance

The effect was correlated to significant wave height (r=0.6, p=0.03), and larger in lateral ship motion, i.e., beam seas. Figure 11 also shows how motion sickness (MSAQ Total score) and "Hold On" percentage are affected differently by the relative wave heading.

MII OBSERVATIONS AND THE GRAHAM TIPPING EQUATIONS

Analysis of the video data resulted in identifying MII events at specific times that were indexed to the corresponding accelerometer data. These data will be reported elsewhere. The Graham Tipping Equations (Graham, 1990) were applied to the accelerometer data to predict the incidence of MIIs, enabling a comparison of predicted and observed MIIs. The Graham Tipping Equations predicted far more MIIs than were observed. The predicted lateral tipping estimate was 47 times greater than the observed MIIs.

MANUAL DEXTERITY: THE FROM

The mean completion times for the FROM manual dexterity test are shown in Figure 12 as a function of significant wave height. Surprisingly, increased wave height did not influence FROM performance in either the standing or stooping positions. Participants were able to perform the task successfully, compensating for ship motion and MIIs.

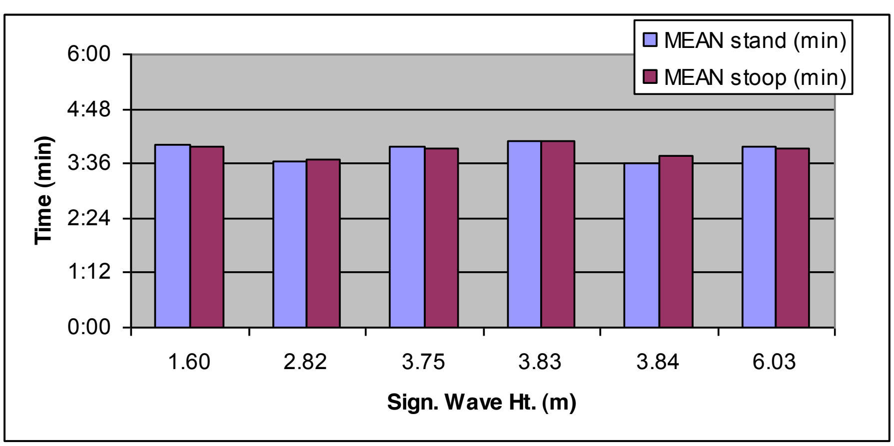

Figure 12. Mean manual dexterity test (FROM) completion times as a function of wave height.

PARTICIPANT COMMENTS

Written comments concerning ship's comfort, motion and motion sickness, were provided by 364 participants (18.24%) on an open-ended question in the survey. The largest portion of these comments focused on the effect of ship's motion. The most common categories of response were:

- Ship Motion Effects 86%
- Motion Sickness 8%
- Uncomfortable Seats 6%

The "ship motion effects" category was decomposed into two categories, Vibration 7.65% and "Loss of balance while standing" 92.35%. Survey participants in the latter category reported using some kind of stable fixed point on the ship to keep their balance, as follows: Railings 60%, Seat 33%, and Wall 7%.

GENERAL DISCUSSION

Motion sickness symptoms were reported in 60-90% of the participants, depending on wave height and relative heading. Significantly less motion sickness ($p<0.001$) was evident in beam seas compared to other relative headings. This result could be related to the roll stabilization afforded by the trimaran hull design, but more data are needed from other vessels before this hypothesis can be confirmed. The comparison of morning and evening test periods revealed significantly higher motion sickness scores on evening trips. The increased incidence of motion sickness symptoms during the "evening" data collection periods is consistent with the interpretation that no visual input from the external environment contributes to visual-vestibular conflict. However, quantification of this effect needs further research because this finding could have been influenced by other factors, such as circadian rhythm, fatigue, and alcohol consumption.

It was interesting that recent experience at sea affected total motion sickness and the gastrointestinal (nausea) scale but did not affect the sopite syndrome. Perhaps adaptation to nausea and sopite are independent processes. More research is needed on the sopite syndrome including causes, mitigations, adaptation processes, and effects on motivation and performance.

The survey data in this study were obtained from paying customers. Although the majority of those who were asked to participate agreed to do so, some passengers declined to participate. Several factors could influence the MSAQ scores—such as the time course of symptom development relative to responding to the questionnaire. On the other hand, some number of severely ill passengers may have been suffering in the restroom and not responding to the questionnaire.

Our analysis showed that the ship's motion, based on relative heading of the seas, affects the passengers in different ways. Forward relative headings (HEAD and BOW seas) resulted in significantly more motion sickness, whereas BEAM seas led to more MIIs.

Although all MSAQ indices were significantly larger during evening test periods, the sopite syndrome index (MSAQ S) showed the least difference between morning and evening test periods. A possible explanation for this finding may be found in the development attributes of sopite syndrome, which can appear relatively quickly in response to a weak or brief stimulus (Lawson and Mead, 1998). In both the morning and evening test periods, the sopite syndrome developed, whereas the rest of symptoms (gastrointestinal, central, and peripheral) were found when ship's motion was more severe or when there was a lack of external visual reference.

The MII analysis is ongoing, but comparison of observed MIIs to the predicted rate of MIIs based on the Graham Tipping Equations showed a very large over estimation. More work is needed in this area, perhaps modeling humans as an adaptive, closed-loop system that actively counteracts imposed forces to maintain posture and equilibrium. For example, Wedge and Langlois (2003) have been making advances in articulated dynamic models of postural stability of humans on ships.

CONCLUSIONS

The motion effects of the *Benchijigua Express* were relatively benign; given that it was operating at speeds in excess of 32 knots and that the participants were unadapted passengers, not crew. Some level of motion sickness was observed in a majority of the passengers.

The availability of an outside view reduces motion sickness incidence and marine engineers can take that into account, especially when designing spaces for unadapted passengers. Also the data indicated that passenger locations more forward of the pitch axis are associated with a higher incidence of motion sickness.

As an MII analysis tool, the "Graham Tipping Equations" (Graham, 1990) greatly over predict MIIs. Advances are needed in modeling postural stability at sea. Railings and other hand-holds are frequently used by passengers as helpful aids to maintain posture and enable locomotion.

The motion of this vessel, even at higher sea states, did not have a negative influence on the performance of manual dexterity tasks, either in the standing or stooping posture.

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